The Role of Ocean Color in Global Climate

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The role of ocean color in the climate system is investigated with a fully coupled ocean, atmosphere, land and ice model. Oceanic shortwave radiation penetration depends on chlorophyll concentration. Removing all chlorophyll from the ocean produces a permanent El Niño state with off-equator chlorophyll being most important. The results imply a positive feedback between chlorophyll concentration and a non-local coupled response in the ocean-atmosphere system.

1. Introduction

The importance of ocean circulation on biological processes and carbon sequestration is well established *Gnanadesikan et al.* [2004]; *Sarmiento and Toggweiler* [1984]; *Watson and Liss* [1998]. While impacts of ocean biology on global scale circulation have been explored they are not well understood *Sweeney et al.* [2005]; *Morel* [1988]; *Manizza et al.* [2005]; *Rosati and Miyakoda* [1988]; *Schneider and Zhu* [1998]; *Murtugudde et al.* [2002]; *Nakamoto et al.* [2001]; *Shell and Nakamoto* [2003]. A number of studies have suggested links between chlorophyll, shortwave absorption and circulation *Siegel et al.* [1995]; *Stramska and Dickey* [1993]. Chlorophyll, a photo-active pigment, absorbs certain bands of radiation primarily in the red and blue/violet region *Siegel and Michaels* [1996]. The specific wavelengths and amounts absorbed depend on the type of chlorophyll and its concentration. Infrared radiation (wavelengths $>$ 700 nm) is absorbed by water itself in the first two meters of the ocean *Manizza et al.* [2005]. Shortwave radiation (which includes ultraviolet and visible light) has the potential to penetrate far deeper. The depth range within the water column over which shortwave energy is absorbed is important in establishing the ocean mixed layer depth (MLD) *Siegel et al.* [1995]; *Stramska and Dickey* [1993]. The effect of including ocean color is to reduce the shortwave penetration depth and the potential for mixing driven by static instability near the base of the mixed layer *Siegel et al.* [1995]; *Stramska and Dickey* [1993]. As a result, the mixed layer shoals, the thermocline strengthens and the effectiveness of turbulence is reduced. Reduction of MLD reduces the heat capacity of the mixed layer and results in the mixed layer properties being more sensitive to atmospheric conditions.

In the absence of other feedbacks, the addition of chlorophyll results in warmer sea surface temperatures (SSTs) and less mixing up of nutrient rich water. This leads to the aesthetically attractive implication that chlorophyll concentrations are self-limiting *Timmerman and Jin* [2002]; *Marzeion et al.* [2005]. However, ocean-only general circulation model (OGCM) studies imply the opposite is true for the equatorial east Pacific. Decreasing the models' shortwave penetration depth results in increased upwelling and surface cooling of a degree or less *Sweeney et al.* [2005]; *Manizza et al.* [2005]; *Schneider and Zhu* [1998]; *Shell and Nakamoto* [2003]; *Nakamoto et al.* [2001]. This study investigates whether coupled feedbacks amplify or damp the changes in ocean-atmospheric circulation induced by ocean biology.

2. Models and experiments

The ocean model used in this study is the Hallberg Isopycnal Model (HIM) *Hallberg* [2003, 2005]. HIM is run at a resolution that is 1° in latitude and longitude, with meridional resolution equatorward of 30° becoming progressively finer, such that the meridional resolution is 3/8° at the Equator. HIM is coupled to the atmosphere, land and ice components used in the GFDL global coupled climate model *Delworth* [2006].

The impact of ocean color on shortwave penetration into the water column is included using an irradiance parameterization proposed by Manizza et al. (2005) *Manizza et al.* [2005]. The scheme parameterizes the effect of ocean color in terms of chlorophyll-a concentrations (Fig 1a). Figure 1b shows the potential heating by the absorption of shortwave radiation as predicted by this scheme as a function of depth and chlorophyll concentration; the heating differential due to increasing chlorophyll concentrations is high in the first few tens of meters *Morel* [1988]. With a much deeper clear-water reference than previous algorithms, there is shortwave induced heating at depths well beyond 100 m. This heating becomes significant when integrated over decadal and larger time-scales.

Initially, two global simulations are run using the simulation protocol for the 1990 control runs with the GFDL coupled climate model *Delworth* [2006] in which aerosols and greenhouse gasses were held constant at modern levels. The experiments for this study were run for 100 years in order to establish surface biases *Gnanadesikan et al.* [2005]. One simulation (*Green*) uses the monthly mean climatology for chlorophyll-a to determine the shortwave penetration depth (Fig. 1a). We utilized satellite chlorophyll from the SeaWiFS monthly composite from 1998-2004. [1]. In the other simulation (*Blue*), chlorophyll-a is set to zero to emulate the shortwave penetration depth of optically pure water. Results are shown as averages over the 100 year time period (Fig. 1b,1c,1d).

3. Results and discussion

While the extra-tropical ocean appeared to follow the relationship described earlier (the addition of chlorophyll leading to shoaling of the mixed layer and surface warming), the substantially cooler *Green* tropical Pacific SSTs (comparable to a permanent La Niña, Fig 1c) coincided with a shallower mixed layer (Fig. 2a). Despite the cooler SSTs, the depth integrated transport of heat out of the tropics is 10 % larger in the *Green* simulation.

To understand why the presence of chlorophyll results in a surface cooling in the equatorial Pacific we examine the steady linearized off-equatorial momentum balance in the mixed layer. Following Sweeney et al. (2005),

$$-fM_y = \frac{\tau_x}{\rho_o} + \int_{MLD}^{\eta} -\frac{1}{\rho_o}\frac{\partial p}{\partial x}dz + R \tag{1}$$

where $-fM_y$ is depth integrated Coriolis force. Here, f is the Coriolis parameter and M_y is the meridional transport, τ_x is the east-west wind stress, ρ_o is a reference density for seawater,$\partial p/\partial x$ is the east-west pressure gradient which is integrated from the surface (η) to the base of the mixed layer (MLD) and R is the residual. By considering the individual terms in this equation we can diagnose possible mechanisms for the increased transport. To limit the amount of coupled adjustment, model averages from the first five years are examined. The terms in equation 1 are calculated from these averages and the differences ($Green - Blue$) plotted in figure 2b. The difference in depth integrated Coriolis force (*Green* and *Blue*) cannot be explained by the difference in the wind stress, it is the wrong sign. Significant differences appear in the geostrophic term (second term RHS of equation 1) when it is integrated over the MLD. The shallower MLD in the *Green* (Fig 2a) simulation results in a weaker equatorward geostrophic acceleration. This, in part, explains the net increase in equatorial poleward meridional acceleration in the *Green* simulation.

The effect of ocean color on the magnitude and phase of the SST seasonal cycle is consistent with previous studies *Schneider and Zhu* [1998]; *Shell and Nakamoto* [2003]. In the *Green* simulation, summer hemisphere SSTs tends to be warmer and in the high latitudes winter hemisphere SSTs cooler (Fig 1b-1c). Additionally, the shallower mixed layer has a smaller heat capacity, leading to an increased sensitivity to seasonal forcing. In the winter hemisphere there is surface cooling in the *Green* simulations due to mixing up of subsurface water that had been shaded (cooled) by the chlorophyll. In some previous studies the chlorophyll-induced winter hemisphere cooling is strong enough that runs with chlorophyll were cooler than the control run experiments over the winter hemisphere *Shell and Nakamoto* [2003]. By contrast, the *Green* simulation remains warmer than the *Blue* throughout the year when a hemispheric average is taken. The difference in hemispherically averaged SST between the ocean color and control runs is systematically 0.2° higher in these coupled model simulations when compared with previous results *Shell and Nakamoto* [2003].

While the pattern of atmospheric response to adding ocean color is consistent with the results of Shell et al. *Shell and Nakamoto* [2003], the magnitude of the response is three to five times larger in this study (Fig. S1-S2). This is due to coupled feedbacks. The equatorial zonal wind strengthens in the runs with chlorophyll. This can be explained, at least in part, by the increased zonal SST gradient set up by the strengthened cold tongue in the equatorial Pacific. The cooler SSTs also result in decreased equatorial convection and a weakened Hadley circulation. Large changes in the mean states of precipitation are confined to the tropics(Fig. 1d). The western Pacific precipitation is shifted westward in *Green* compared to *Blue*, consistent with the changes in the local SSTs(lower temperatures implying less convection).

It might be suspected that the high concentration of chlorophyll along the eastern equatorial Pacific is responsible for the increased upwelling in that region. However, the off-equator depth-integrated meridional acceleration differences shown in figure 2b suggest that the cause for this cooling could be nonlocal (off equator). To test this, three additional simulations are run where values falling between latitudinal bands in the Pacific are set to zero; 5°N and 5°S (ZE), 5°N to 10°N and 5°S to to 10°S ($Z5\_10$) and 5°N to 20°N and 5°S to to 20°S ($Z5\_20$).

The ocean-atmosphere patterns shown in the $Green - Blue$ mean state differences develops and persists in the $Z5\_10$ and $Z5\_20$ but not the zero-ed equator (ZE) simulation (Fig 3). The cooling of the Equatorial Pacific cold tongue by ocean color is not due to local mechanisms.

Figure 2c summarizes the proposed mechanism for the equatorial Pacific ocean-atmosphere response to the presence of chlorophyll. The ocean's immediate response to the presence of chlorophyll is two-fold- a shoaling of MLD and warming of SST, and a cooling of subsurface water due to chlorophyll shading. Assuming that at least initially the wind stress is the same (Fig. 2b), equation 1 implies a net increase in poleward surface transport and consequently equatorial surface divergence (Fig 2b). Increased equatorial upwelling follows. This increase in upwelling combined with the cooler subsurface water (due to shading) leads to cooler equatorial SSTs, overwhelming the direct shortwave heating tendency in the mixed layer (Fig. 1b,1c). The atmosphere adjusts accordingly. The Hadley circulation weakens, precipitation shifts westward (Fig. 1d) and the Walker circulation shifts and intensifies *Bjerknes* [1969a]. The ocean adjusts to atmosphere, following the classic Bjerknes feedback *Neelin et al.* [1998]; *Bjerknes* [1969b]. However, the increased upwelling does not lead to increased formation or volume of light subtropical water (as occurs during an El Niño). This may be due to shading by the off-equator chlorophyll. The weak shoaling of the mixed layer (Fig 2a) and the results of the second set of simulations imply that the increase in divergence is established off-equator.

4. Conclusions

Two new and important implications arise out of this study. First, the chlorophyll responsible for the cooling and increased upwelling in the equatorial Pacific is located off-equator. These regions contain low chlorophyll concentrations so that colored dissolved organic matter, which has a much longer lifetime than phytoplankton, may play a larger role in setting the optical properties. The increased upwelling in the equatorial Pacific implies an increase in available nutrients for chlorophyll-producing phytoplankton. The ocean-atmosphere response to the off-equator chlorophyll suggests possible positive feedbacks when active biology is included. The second implication arises from the connection between off-equator MLD and equatorial SST shown in the model results. The trigger for this mechanism need not be limited to shortwave penetration. Any phenomenon that results in a large enough perturbation in mixed layer depth in the off-equator region could be a viable candidate. Many climate models show a cold tongue bias in the eastern Pacific *Davey et al.* [2000]. This could be due to underestimation of mixing in the off equatorial regions.

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Notes

1. Courtesy of the Goddard Earth Sciences Distributed Active Archive Center: http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/index.html

References

Bjerknes, J., A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature, *Tellus*, *18*, 820–829, 1969a.

Bjerknes, J., Atmospheric teleconnections from the equatorial pacific, *Mon. Wea. Rev.*, *97*, 163–172, 1969b.

Davey, M. K., M. Huddleson, K. R. Sperber, P. Braconnot, F. Bryan, D. Chen, R. A. Colman, C. Cooper, U. Cubasch, P. Delecluse, D. Dewitt, L. Fairhead, G. Flato, C. Gordon, T. Hogan, M. Ji, M. Kimoto, A. Kitoh, T. R. Knutson, M. Latif, H. L. Treut, T. Li, S. Manabe, C. R. Mechoso, G. A. Meehl, S. B. Power, R. Roeckner, L. . Terray, A. Vintzileos, R. Voss, B. Wang, W. M. Washington, I. Yoshikawa, J. Yu, S. Yukimoto, and S. E. Zebiak, Stoic: a study of coupled model climatology and variability in tropical ocean regions, *Clim. Dyn.*, *18*, 403–420, 2000.

Delworth, T. L., Gfdls cm2 global coupled climate models:part 1. formulation and simulation characteristics,, *J. Clim.*, *19*, 645–674, 2006.

Gnanadesikan, A., J. P. Dunne, R. M. Key, K. Matsumoto, J. L. Sarmiento, R. D. Slater, and P. S. Swathi, Oceanic ventilation and biogeochemical cycling: Understanding the physical mechanisms that produce realistic distributions of tracers and productivity, *Glob. Biochem. Cyc.*, *18*, GB4010, 2004.

Gnanadesikan, A., K. W. Dixon, S. M. Griffies, V. Balaji, M. Barreiro, J. A. Beesley, W. F. Cooke, T. L. Delworth, R. Gerdes, M. J. Harrison, I. M. Held, W. J. Hurlin, H.-C. Lee, Z. Liang, G. Nong, R. C. Pacanowski, A. Rosati, J. Russell, B. L. Samuels, Q. Song, M. J. Spelman, R. J. Stouffer, C. O. Sweeney, G. Vecchi, M. Winton, A. T. Wittenberg, F. Zeng, and R. Zhang, Gfdls cm2 global coupled climate models-part 2: The baseline ocean simulation, *J. Climate*, *19*, 675–697, 2005.

Hallberg, R., The suitability of large-scale ocean models for adapting parameterizations of boundary mixing and a description of a refined bulk mixed layer model, *Proceedings of the 2003 Aha Hulikoa Hawaiian Winter Workshop*, pp. 187–203, 2003.

Hallberg, R., A thermobaric instability of lagrangian vertical coordinate ocean models, *Ocean Modelling*, *8*, 279–300, 2005.

Manizza, M., C. L. Quere, A. Watson, and E. T. Buitenhuis, Bio-optical feedbacks amoung phytoplankton, upper ocean physics and sea-ice in a global model, *Geophys. Res. Let.*, *32*, L05,603, 2005.

Marzeion, B., A. Timmerman, R. Murtugudde, and F. Jin, Bio-physical feedbacks in the tropical pacific, *J. Climate*, *18*, 58–70, 2005.

Morel, A., Optical modeling of the upper ocean in relation to its biogenous matter content (case-i waters)., *J. Geo. Res.*, *93*, 10,749–10,768, 1988.

Murtugudde, R., J. Beauchamp, C. R. McClain, M. Lewis, and A. Busalacchi, Effects of penetrative radiation on the upper tropical ocean circulation, *J. Climate*, *15*, 470–486, 2002.

Nakamoto, S., S. P. Kumar, J. M. Oberhuber, J. Ishizaka, K. Muneyama, and R. Frouin, Response of the equatorial pacific to chlorophyll pigment in a mixed layer isopycnal ocean general circulation model, *Geophys. Res. Letters*, *28*, 2021—2024, 2001.

Neelin, J. D., D. S. Battisti, A. C. Hirst, F. Jin, Y. Wakata, T. Yamagata, and S. Zebiak, ENSO theory, *J. Geo. Res.*, *103*(C), 14,261–14,290, 1998.

Rosati, A., and K. Miyakoda, A general circulation model for upper ocean simulation, *J. Phys. Oceanogr.*, *18*, 1601–1626, 1988.

Sarmiento, J. L., and J. R. Toggweiler, New model for the role of the oceans in determining atmospheric pco2, *Nature*, *308*, 621–624, 1984.

Schneider, E., and Z. Zhu, Sensitivity of the simulated annual cycle of sea surface temperature in the equatorial pacific to sunlight parameterization, *J. Climate*, *11*, 1932–1950, 1998.

Shell, K. M., and S. Nakamoto, Atmospheric response to solar radiation absorbed by phytoplankton, *J. Geo. Res.*, *108*, 1–8, 2003.

Siegel, D. A., and A. F. Michaels, Quantification of non-algal light attenuation in the sargasso sea: Implications for biogechemistry and remote sensing, *Deep Sea Res. II*, *43*, 321–345, 1996.

Siegel, D. A., R. R. Bidgare, and Y. Zhou, Solar radiation, phytoplankton pigments and the radiant heating of the equatorial pacific warm pool, *J. Geo. Res.*, *100*, 4885–4891, 1995.

Stramska, M., and T. D. Dickey, Phytoplankton bloom and the vertical thermal structure of the upper ocean, *J. Mar. Res.*, *51*, 819–842, 1993.

Sweeney, C., A. Gnanadesikan, S. Griffies, M. Harrison, A. Rosati, and B. Samuels, Impacts of shortwave penatration depth on large-scale ocean circualtion heat transport, *J. Phys. Oceanogr.*, *35*, 1103 – 1119, 2005.

Timmerman, A., and F. Jin, Phytoplankton influences on tropical climate, *Geophys. Res. Letters*, *39*, 10.10,129/2002GL15,434, 2002.

Watson, A. J., and P. S. Liss, Marine biological controls on climate via the carbon and sulphur geochemical cycles, *Philos. trans. R. Soc*, *353*, 41–51, 1998.

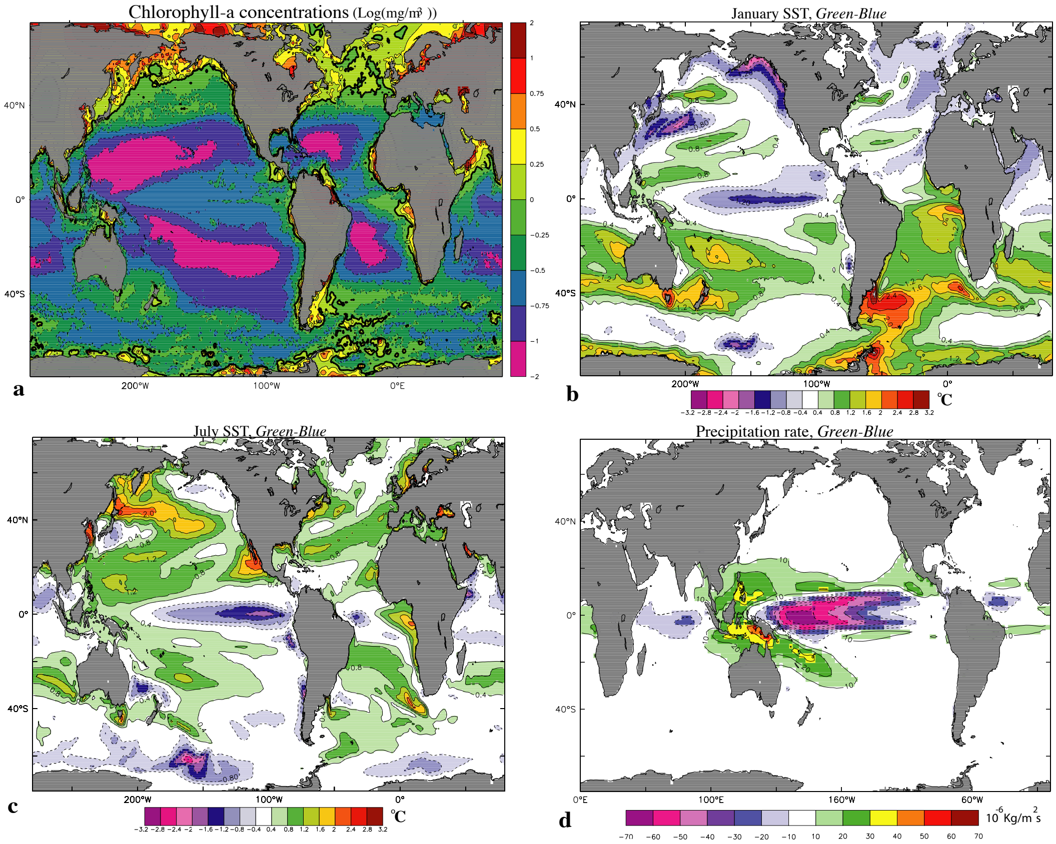

Figure 1. Annual maximum of SeaWiFS surface chlorophyll-a concentrations (a). Monthly mean SST difference between *Green* and *Blue* experiments for January (b) and July (c)and precipitation rate (d).

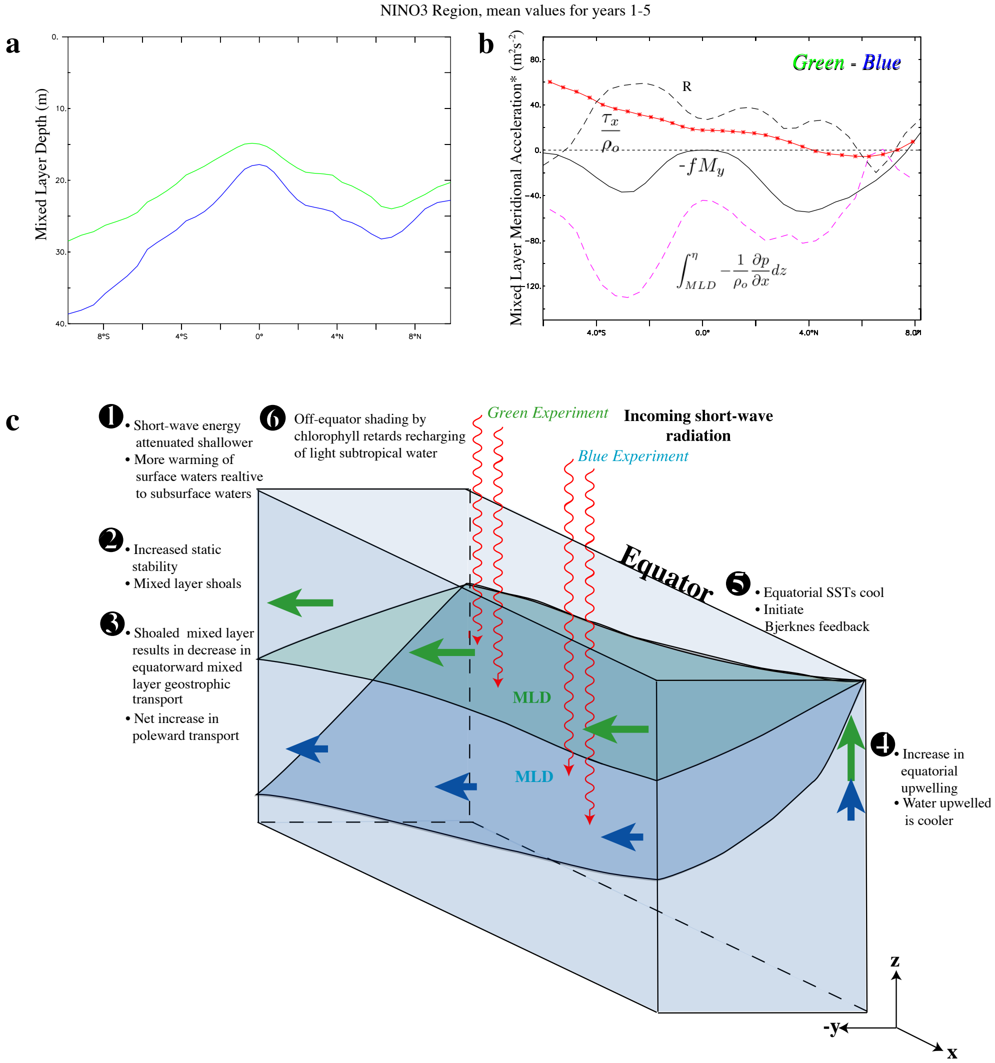

Figure 2. Mean properties for years 1-5 in the 10°S to 10°N region averaged 90°W to 150°W. Green lines are the *Green* simulation and blue lines are the *Blue*. Mixed layer depth (a). *Green* – *Blue* terms in equation 1 from model averages. The black thick-dasehed line is the residual of the differences. (b). Cartoon depicting Equatorial Pacific response to the addition of chlorophyll (c). (*-depth integrated acceleration).

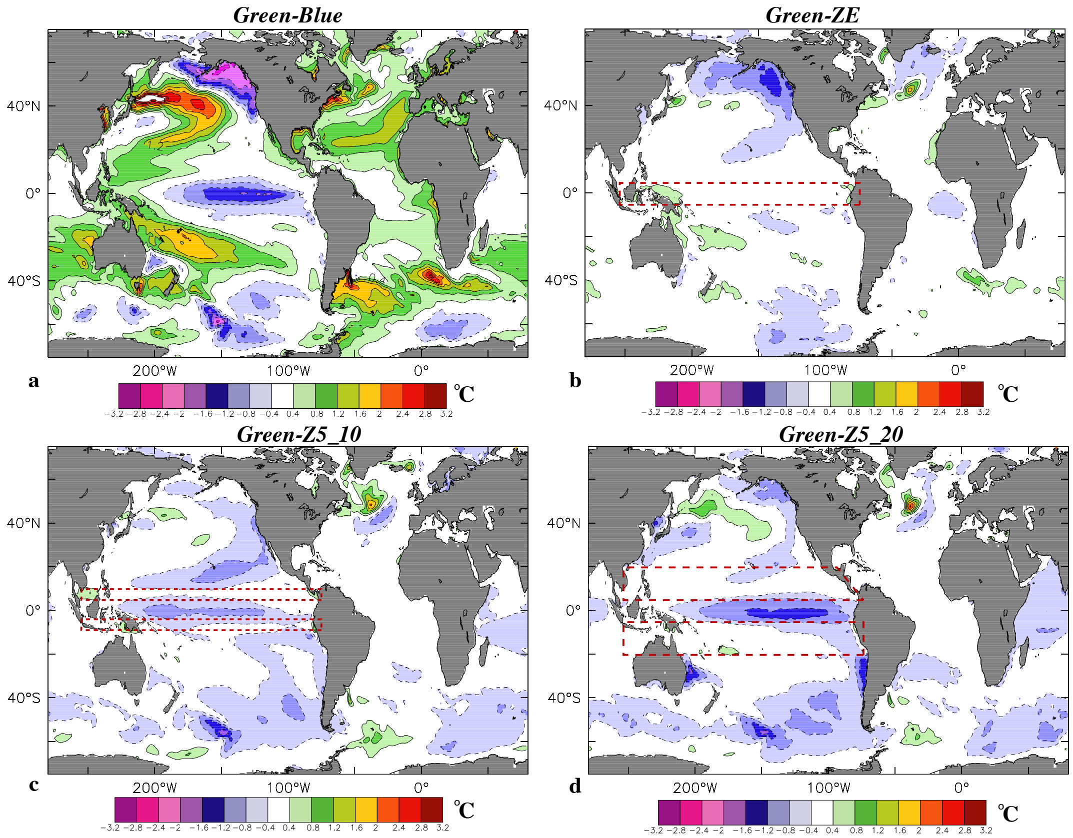

Figure 3. Mean SST difference (for years 1-20) between *Green* and simulations where chlorophyll has been removed in the regions indicated by the dashed boxes: Globally (a), 5S to 5N (b), 5N to 10N and 5S to 10S (c) and 5N to 20N and 5S to 20S (d).

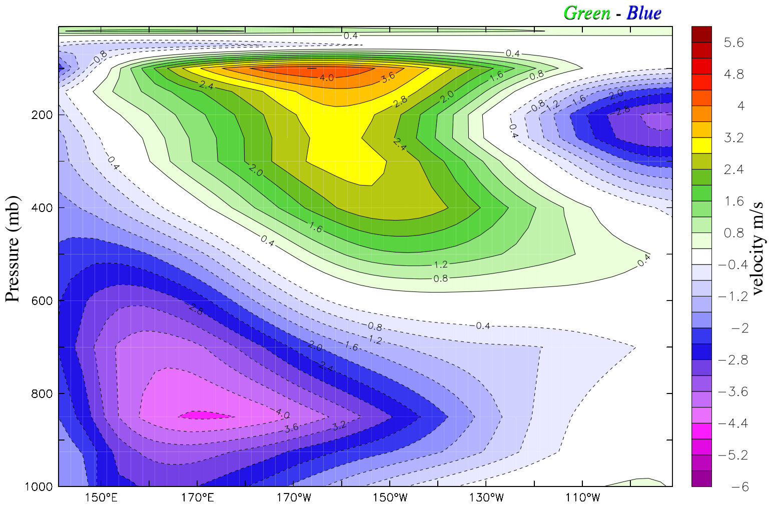

Figure 4. Supplemental: Figure S1. 100 year mean zonal wind velocities (*Green* – *Blue*) for the region 140E-90W, 5N-5S. The velocity differences indicate a strengthening in the Walker circulation with the addition of chlorophyll.

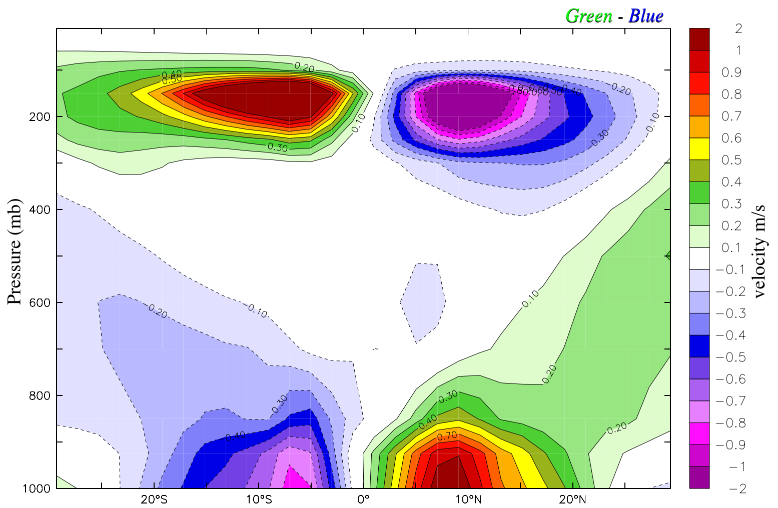

Figure 5. Supplemental: Figure S2. 100 year mean meridional wind velocities (*Green* – *Blue*) for the region 140E-90W, 30N-30S. The velocity differences indicate a weakening in the Hadley circulation with the addition of chlorophyll.